DEVELOPING 3D GEOLOGICAL FRAMEWORKS THROUGH VOLCANIC FACIES ANALYSIS AND INTEGRATED LITHOGEOCHEMISTRY AT THE SPUR PROJECT, EAST LACHLAN, NSW, AUSTRALIA

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Key Words: Spur-Consols, volcanic facies architecture, geochemistry, 3D modelling, Molong Volcanic Belt, Macquarie Arc, Eastonian uplift, tectonics

INTRODUCTION

Spur and Consols are emerging gold deposits in the Macquarie Arc of central New South Wales, recently discovered by Waratah Minerals. Systematic diamond drilling is currently underway to support a maiden Mineral Resource Estimate. This has generated a dense three-dimensional dataset through the volcanic succession.

Drill core samples have been analysed using modern four-acid digest lithogeochemistry providing a high-density geochemical dataset across a substantial volume of the Cargo Volcanics. This is a great opportunity to build on the work of Simpson et al. (2007) who documented the volcanics of the Cargo Complex through regional-scale mapping and reconnaissance sampling, but only had limited diamond drill core available from the early-stage exploration drilling of that time.

This contribution presents a facies-led workflow for building three-dimensional geological frameworks in ancient volcanic successions. The workflow first reconstructs the preserved volcanic architecture of the host succession, then uses that architecture as a scaffold for integrating lithogeochemistry, alteration, mineralisation, structure and intrusive relationships. This paper focuses on methodology, volcanic facies architecture, lithogeochemistry, 3D modelling, and regional implications for the Cargo Complex and the broader Macquarie Arc. Further details on project history and deposit characteristics are provided by Askew (this volume).

REGIONAL SETTING

The Macquarie Arc of the Lachlan Orogen in central New South Wales comprises three major, structurally bounded, meridional mafic volcanic belts separated by Siluro-Devonian basins. From west to east, these are the Junee-Narromine, Molong, and Rockley-Gulgong Volcanic Belts. The belts are widely regarded as the structurally dismembered remnants of a once contiguous intra-oceanic island arc that remained outboard of Gondwana throughout the Ordovician (Glen et al., 1998; Percival and Glen, 2007; Fergusson and Colquhoun, 2018; Aitchison and Buckman, 2012). The Macquarie Arc docked onto the Gondwanan margin during the 440 Ma (Phase 1) to 430 Ma (Phase 2) Benambran Orogeny (Glen et al., 2007). Post-orogenic extension was accompanied by alkalic-shoshonitic magmatism and the development of alkalic porphyry-epithermal systems (Cooke et al., 2007), including the pencil porphyry deposits of the Cadia (Fox et al., 2015; Harris et al., 2014., Wilson, 2003) and Northparkes districts (Lickfold et al., 2007; Pacey et al., 2019; Wells et al., 2020).

Previous correlations across the volcanic belts, based on geochemistry, geochronology and biostratigraphy, interpreted two volcanic hiatuses at approximately 475-460 Ma and a more temporal and spatially variable volcanic hiatus across the Ordovician-Silurian boundary around ~ 455-440 Ma (Percival and Glen, 2007). More recent geochronology has reduced

the inferred temporal and geographic extent of these hiatuses and, in some areas, has called their existence into question (Kemp et al., 2020). Within the Molong Volcanic Belt, the younger hiatus is locally expressed by volcanic and volcaniclastic successions of the Kenilworth Group passing upward into geographically extensive Barrajin Group limestones, interpreted to reflect regional uplift during the Eastonian [Crawford et al., 2007; Simpson et al., 2007]. The Barrajin Group limestones are overlain, unconformably at many localities, by deep-water sedimentary successions of the Cabonne Group (Percival and Glen, 2007).

Simpson et al. (2007) assigned the Cargo Volcanics to the Kenilworth Group and mapped conglomerates containing rounded cobbles resembling the Cargo Volcanics that were in turn, overlain by Barrajin Group limestones. They suggested that resolving the volcanic and geochemical evolution of the Cargo Volcanics may provide key insights into the tectonic evolution of the Macquarie Arc immediately preceding Eastonian uplift and the subsequent volcanic hiatus. The extensive drill core and high-density lithogeochemical dataset at Spur-Consols provides an opportunity to reassess the volcanic evolution at deposit scale and to consider its broader tectonic implications.

METHODS

Rationale

Ancient volcanic basins preserve volcano-sedimentary successions that are commonly overprinted by intrusive, alteration-mineralisation, metamorphic, and deformational events. The methodology applied here seeks first to look through these later overprints and establish the primary volcanic architecture of the host succession. The underlying premise is that volcanic facies architecture forms the primary geological scaffold that may influence the distribution, geometry, and preservation of later features, including intrusion emplacement, fluid flow, alteration zonation, mineralisation, and deformation.

The workflow begins with blind graphic logging of drill core. Crystal cargoes, textures, contacts, grading relationships, clast populations, and sedimentary structures, are used to interpret the setting, and depositional and emplacement processes, without reference to assays, lithogeochemistry, alteration-indices, structural interpretations or modelled domains. The objective is to produce a down-hole vertical succession of lithofacies, interpreted solely from physical evidence in drill core, that can be tested against independent datasets. This approach builds on a methodology developed by the author for 3D volcanic reconstructions at the Cowal Gold deposit (Ila'ava et al., 2024, 2025).

Blind graphic logging and iterative data integration

A total of 6.1 km of detailed graphic logging has been completed across 14 drill holes from the Spur and Consols deposits. Graphic logs were hand drawn digitally on a Remarkable tablet using A4 logging templates at a scale of 50 m per page. Because the logs are digital and can be exported as consistent scalable vector graphic (SVG) files, downstream automated outputs can be produced based on the graphic logs.

For example, an R script was developed to automatically overlay lithogeochemical interpretations and strip logs of Au, As, Cu and magnetic susceptibility onto the graphic logs (Fig. 1). With these automated R script driven outputs, the core premise of the workflow can effectively be contained within a single drill hole: the volcanic succession is first interpreted independently through detailed graphic logging, then complementary datasets are overlaid to stress-test, refine and revise the interpretation. Mismatches between the graphic logs and

datasets are productive points of interrogation rather than issues to be overlooked during modelling.

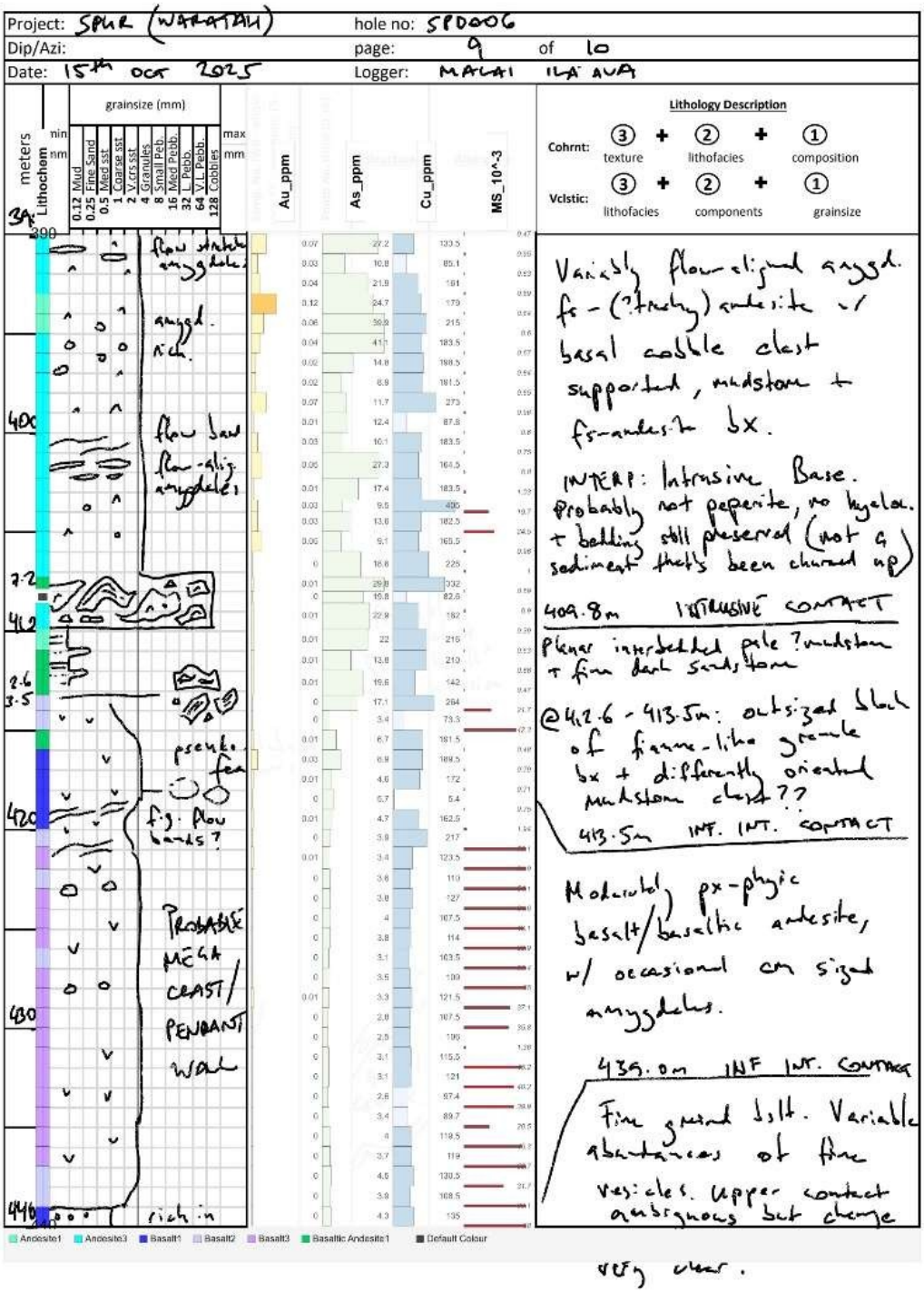

Figure 1: Example of blind graphic logging from SPD006, 390-440m, completed at 50m per A4 page on a Remarkable Tablet. Lithogeochemical populations, Au, As, Cu, and magnetic susceptibility were added later using an R script, allowing core-derived facies interpretations to be interrogated against independent datasets.

Summary lithofacies at Spur-Consols

The Spur-Consols deposits are dominated by thick, massive coherent volcanic units that transition to monomict clast supported breccias with lobate and/or blocky clasts, generally interpreted as massive and pillowed lavas passing to auto-brecciated and hyaloclastite margins. There is some variety in crystal cargoes; increases in relative feldspar abundance generally corresponds to changes in the lithogeochemical compositions defined by Sc, V, Ti abundance, ranging from aphyric basalt, to sparsely-feldspar phyric basaltic andesite, to feldspar-glomerophyric andesites. Sedimentary units such as volcaniclastic turbidites or planar stratified mudstones are volumetrically minor but provide key evidence for interpreting a below wave base, deep marine setting for the volcanics.

In comparing both deposits, Consols has a much thicker preserved succession of massive coherent units that pass up vertically to wavy flow banded units that, from the geochemistry, correspond to evolved compositions like ‘dacite’. Consols is interpreted as a more vent proximal domain, dominated by thick, massive coherent lavas or sub-volcanic intrusions. By contrast, coherent units at Spur that are interpreted as lavas, appear to be thinner (10-20m downhole thickness) with tabular geometries, and pass up to pillows or hyaloclastite more regularly than at Consols. At Spur, a well-preserved ~40 m thick succession comprising sediment-matrix andesite breccia, coherent feldspar-glomerophyric andesite and vesiculated hyaloclastite tops is interpreted as a submarine lava dome. In the context of the broader volcanic architecture, this is interpreted as a satellite or parasitic dome, in the medial to distal aprons of a submarine stratocone.

Complicating that basin architecture are thick (10’s of m’s thick) occurrences of aphyric basalt with varied vesicularity. At drill core scale, it is possible to track the aphyric, vesiculated texture around other clasts. Where these features have been drawn in graphic logs, this is interpreted as an aphyric basalt sill, stoping out pendants of a precursor volcanic succession. At times the aphyric basalt is clearly associated with lobate / pillowed clasts and in-situ hyaloclastite sheets. Because of alteration induced pseudobreccias, it can be very challenging to interpret whether an interval of aphyric basalt is a sill, a shallow sub-volcanic intrusion, or has vented to sea floor as a lava and / or magma fountaining deposit. Distinguishing between sill emplacement, shallow sub-volcanic intrusion and erupted basaltic deposits remains an important interpretive challenge as drilling progresses.

In summary, Consols appears to be a coherent dominated, relatively vent-proximal ‘block’ of a submarine stratovolcano, with Spur representing the medial- to distal- slopes with parasitic lava domes. This architecture has then had the aphyric basalt ‘event’ superimposed on it, that is generally emplaced as a concordant tabular sill, but in places is clearly deposited as a lava / magma fountaining deposit.

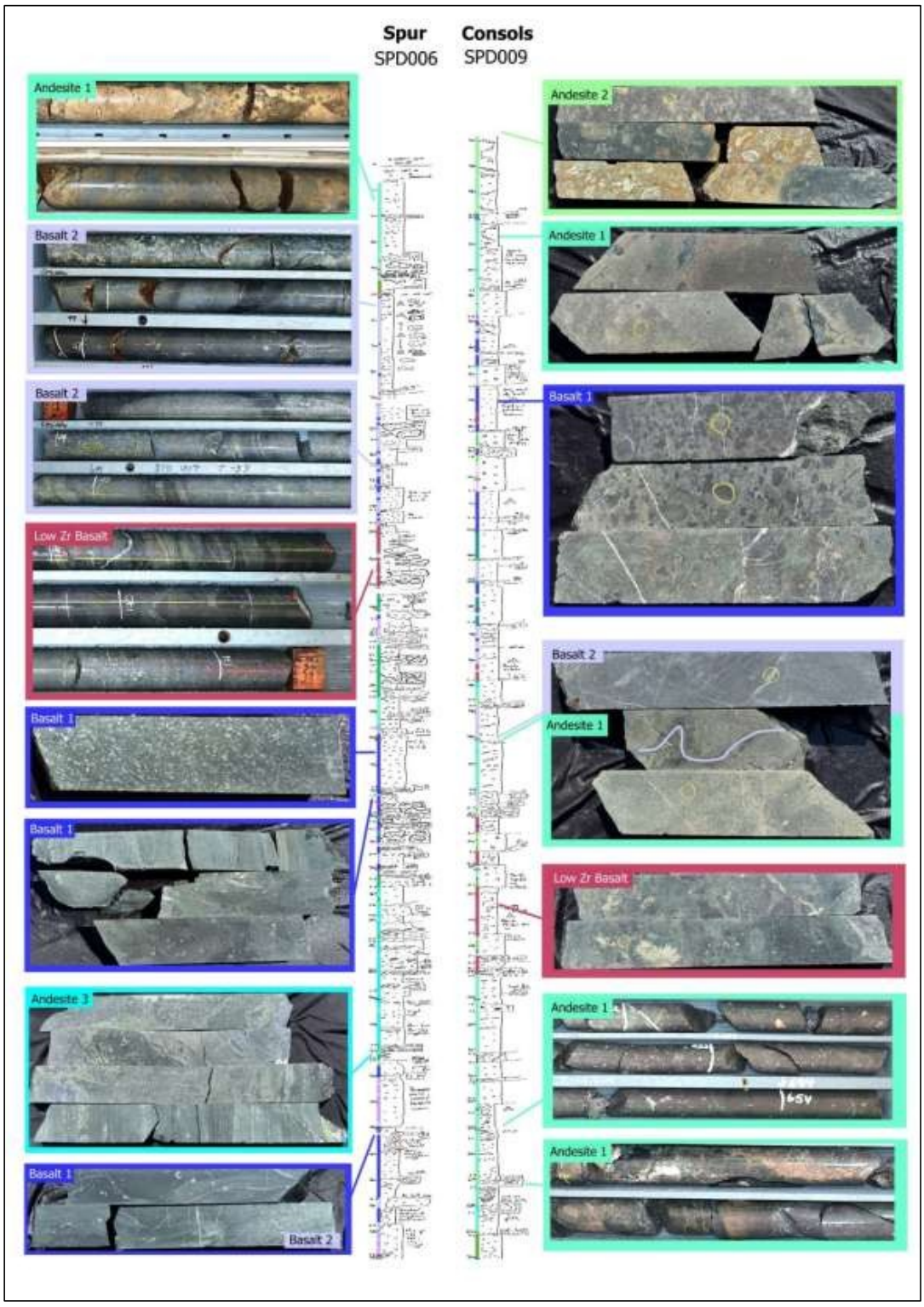

Figure 2: Graphic logs from representative drillholes at Spur (SPD006) and Consols (SPD009), with callout photographs showing volcanic and sedimentary textures. Photographs are colour coded to show how these samples were classified in the lithogeochemistry. Note the variation in textures and crystal cargoes within a given lithogeochemical unit.

Lithogeochemistry analysis

Four-acid digest lithogeochemistry data (n = 34,576) were interpreted using ioGAS. Bivariate plots of immobile high-field-strength elements (HFSE) were used to identify co-magmatic geochemical populations. The ratios Nb/Zr and Y/Zr proved particularly useful for discriminating geochemical populations and for evaluating potential tectono-magmatic affinity (Fig 3).

The interpreted volcanic succession lies largely within a 0.02-0.03 Nb/Zr population, which was subdivided into provisional lithogeochemical units using elements such as Sc, Ti and V as proxies for relative maficity (Halley, 2020). Viewing these units in Leapfrog revealed laterally continuous layers and domains in three-dimensional space. When integrated with graphic logging, these lithogeochemical domains provided a scalable framework for geological modelling.

The blind graphic logging generally correlated with lithogeochemical domains, but several significant mismatches required further interpretation. To reconcile these mismatches, the working hypothesis was that individual lithogeochemical units may represent discrete magmatic, depositional and/or emplacement events. Graphic logging then provided the physical context to assess whether a single lithogeochemical population was expressed through different coherent textures, volcaniclastic facies, intrusive equivalents, or deposit/emplacement processes.

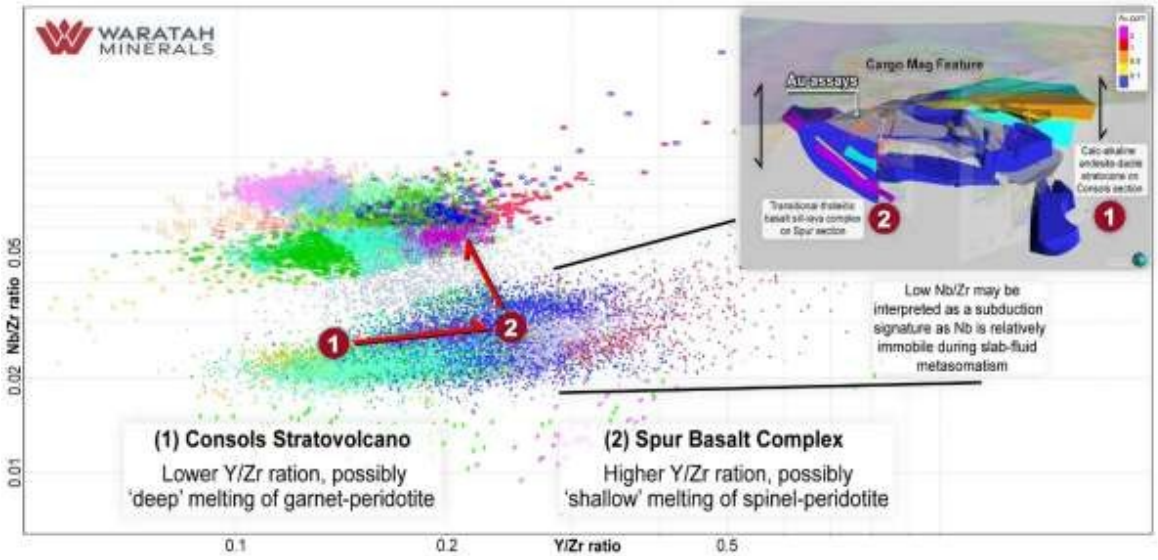

Figure 3: Summary Nb/Zr versus Y/Zr plot for the Spur-Consols lithogeochemical dataset. The plot highlights a low Nb/Zr volcanic population and inferred progression from calc-alkaline andesite-dacite volcanic rocks associated with the preserved remnants of the 'Consols stratocone' (1) towards more mafic transitional-tholeiitic compositions associated with the Spur basalt sill-lava complex (2). Inset – 3D model of volcanic architecture (see Figure 4).

Cross Sections and 3D Modelling

Detailed cross sections were constructed for both Spur and Consols by integrating graphic logging, lithogeochemical interpretations, and geological observations from drill core. Bedding measurements (n = 402) were used to generate isosurfaces in Leapfrog that provided a visual

reference for the average S0 orientation which assisted cross-section interpretations of the stratigraphic architecture.

Graphic logging, lithogeochemical interpretations and bedding isosurfaces collectively underpinned multiple iterations of a three-dimensional geological model. With its extensive spatial distribution and sample density, the lithogeochemical dataset proved particularly effective for scaling lithofacies observations from individual drill holes into a deposit-scale framework. The current interpretation is best described as a working geological model that is iteratively constrained by lithogeochemistry and calibrated by targeted lithofacies observations.

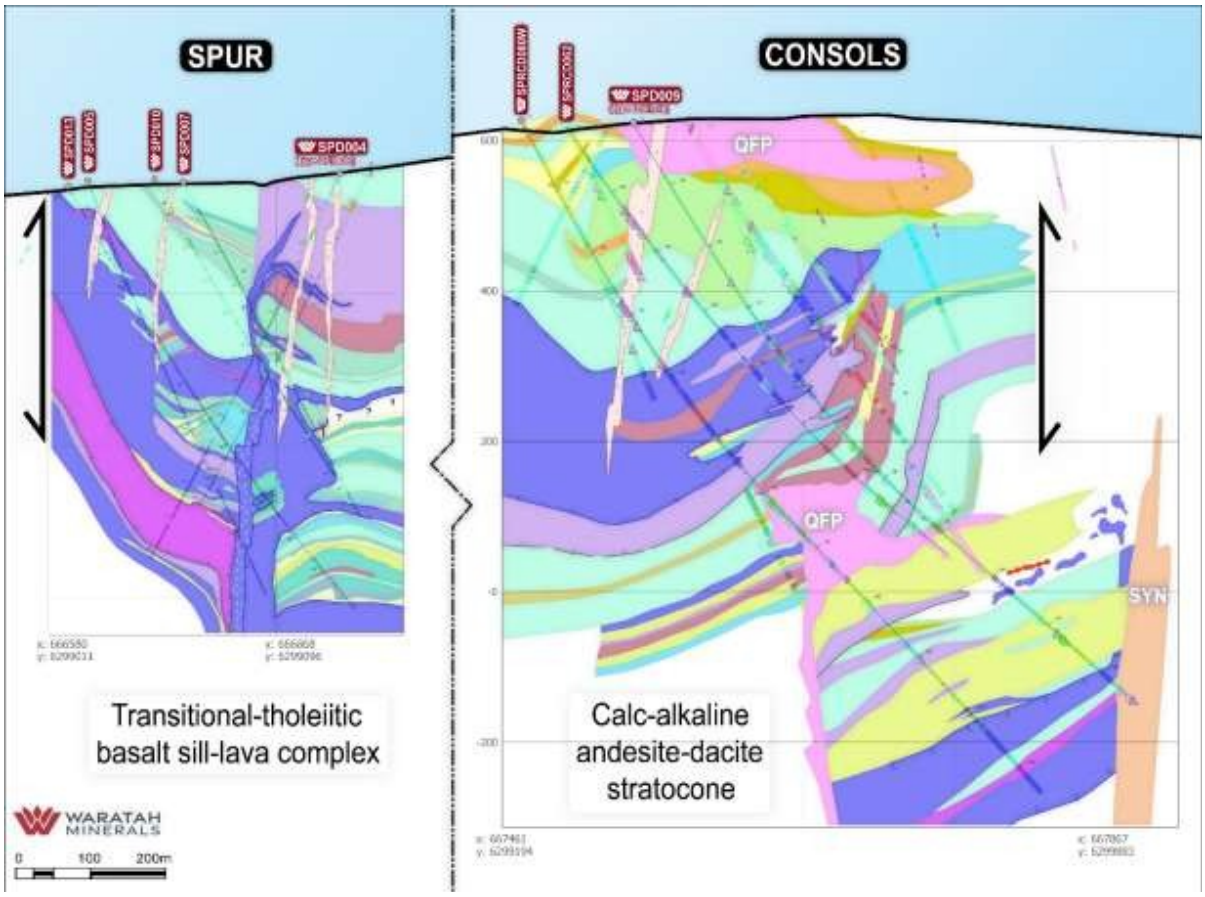

Figure 4: Interpreted representative sections through Spur and Consols. The Consols section is interpreted to preserve a calc-alkaline andesite-dacite stratocone, whereas the Spur section is dominated by a transitional-tholeiitic basalt sill-lava complex that dissects, intrudes and/or overlies the older volcanic architecture.

RESULTS AND SYNTHESIS

The Spur-Consols deposits are interpreted to preserve remnants of a submarine calc-alkaline stratocone (Simpson et al 2007), likely centred on Consols that has subsequently been dissected, intruded and/or overlain by basaltic sills and lavas displaying transitional to tholeiitic affinities, most clearly developed at Spur (Fig. 3 and 4).

At a tectonic scale, the preserved succession may record a transition from calc-alkaline magmatism generated by hydrous flux melting beneath an arc-front, to more mafic transitional-tholeiitic magmatism associated with shallower decompression melting, potentially in a rear-arc or extensional setting. If correct, this transition occurred stratigraphically below the interpreted Eastonian uplift surface and may provide new insight into the tectono-magmatic evolution of the Cargo Complex and broader Molong Volcanic Belt immediately prior to the regional volcanic hiatus.

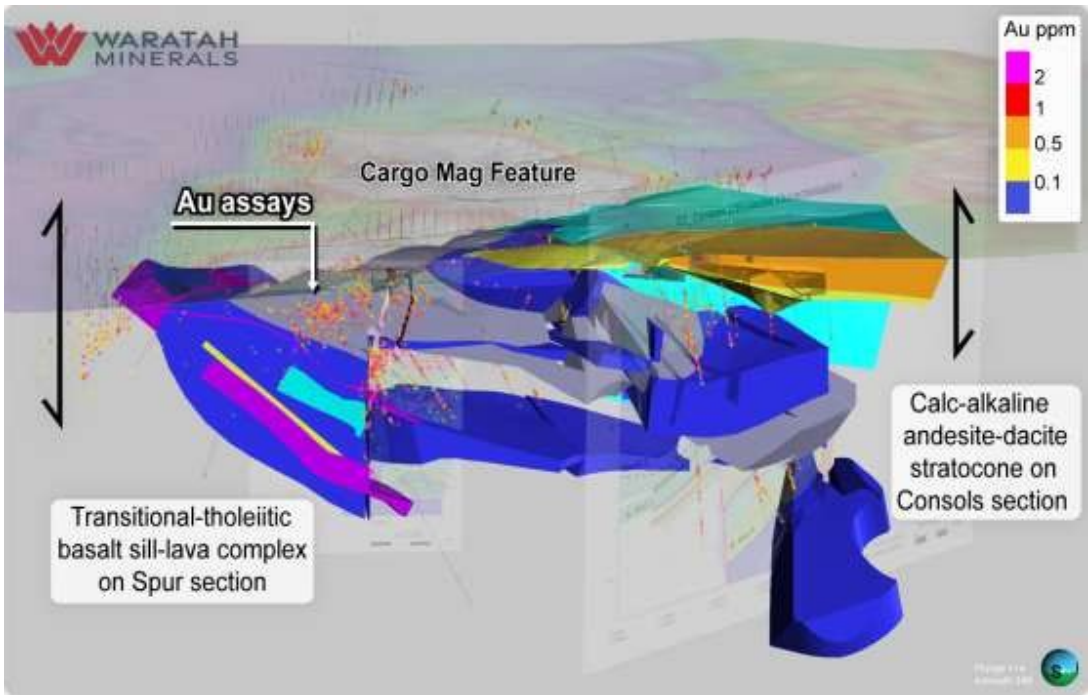

Figure 5: Preliminary three-dimensional geological framework for Spur-Consols, integrating lithogeochemical domains, interpreted cross sections, drill holes, Au assays and geophysical context. The model highlights the interpreted relationship between the Consols calc-alkaline stratocone and the Spur transitional-tholeiitic basalt sill-lava complex.

DISCUSSION

The Spur-Consols workflow demonstrates the value of treating volcanic facies architecture as the primary framework for interpreting complex, overprinted volcanic-hosted mineral systems. In this approach, drill core observations are not used merely to assign lithological codes, but to reconstruct depositional and emplacement processes, establish stratigraphic relationships and provide geological context for lithogeochemical, structural, alteration and mineralisation datasets.

A key outcome of the workflow is that lithogeochemical domains can be interpreted geologically rather than treated only as statistical or compositional populations. Where lithogeochemical units correlate with logged facies, they provide a powerful means of projecting observed volcanic architecture between drill holes and into three-dimensional space. Where mismatches occur, they become useful points of interrogation, prompting reassessment of whether individual geochemical populations represent discrete magmatic events, facies variations within a broader eruptive unit, intrusive equivalents, alteration effects, or structural repetition.

At Spur-Consols, this integrated approach supports interpretation of a submarine calc-alkaline volcanic centre, centred on Consols, that was subsequently dissected and intruded and/or overlain by more mafic transitional-tholeiitic basaltic sills and lavas, most clearly developed at Spur. This interpretation has implications beyond the deposit scale. If the transition from calc-alkaline to transitional-tholeiitic magmatism records a shift from deeper hydrous flux melting beneath a volcanic front to shallower decompression melting in a rear-arc or extensional setting, then the Cargo Volcanics may preserve an important record of tectono-magmatic reorganisation immediately prior to Eastonian uplift in the Molong Volcanic Belt.

More broadly, the study highlights how high-density lithogeochemistry, when calibrated against detailed volcanic facies logging, can be used to construct iterative three-dimensional geological frameworks in ancient volcanic successions. Such frameworks provide a practical basis for testing mineralisation controls, refining exploration models, identifying geological uncertainty and communicating interpretations across project teams.

CONCLUSIONS

- Blind graphic logging provides an independent volcanic facies framework that can be tested against lithogeochemistry, assays, structure, alteration and geophysical datasets.

- High-density lithogeochemistry provides an effective means of scaling core-based facies observations into a deposit-scale three-dimensional model.

- The Spur-Consols succession is interpreted to record a coherent dominated, calc-alkaline andesite-dacite submarine stratocone, likely centred on Consols, later dissected, intruded and/or overlain by a transitional-tholeiitic basalt sill-lava complex most clearly developed at Spur.

- This transition may record tectono-magmatic reorganisation from a volcanic front, to a rear arc or extensional setting in the Cargo Complex immediately prior to Eastonian uplift in the Molong Volcanic Belt and Macquarie Arc.

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